

interplanetary causes of great and superintense magnetic storms

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Interplanetary causes of great and superintense magnetic storms

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Abstract. We examine possible interplanetary mechanisms for the creation of the largest magnetic storms at the Earth. We consider the effects of interplanetary shock events on magnetic cloud and sheath plasma. We also examine the effects of a combination of a long-duration southward sheath magnetic field, followed by a magnetic cloud B_s event. Examination of profiles of the most intense storms from 1957 to the present indicate that the latter (double $IMF B_z$ events) is the most probable cause of the largest D_{ST} events.

1 Introduction

The purpose of this paper is to examine the causes of the largest magnetic storms at Earth. We know the **energy** transfer mechanism from the solar wind to the magnetosphere for magnetic storms is magnetic reconnection between the interplanetary magnetic fields and the Earth's fields, where the interplanetary dawn-dusk electric field is given by $V_{sw} \times B_s$ (Dungey, 1961; Gonzalez et al., 1994). In the above expression, V_{sw} is the solar wind velocity and B_s is the southward component of the interplanetary magnetic field (IMF). However, there has been little effort placed [o date on understanding the detailed causes of the very largest magnetic storms. Are the velocities unusually high? Are the magnetic fields unusually intense or do both the velocity and magnetic fields have to be large to create superintense storms? Are double or triple shock events creating very high magnetic fields? Or are [here other causes of these unusually intense storm events?

2 Sheath/ICME Magnetic Fields

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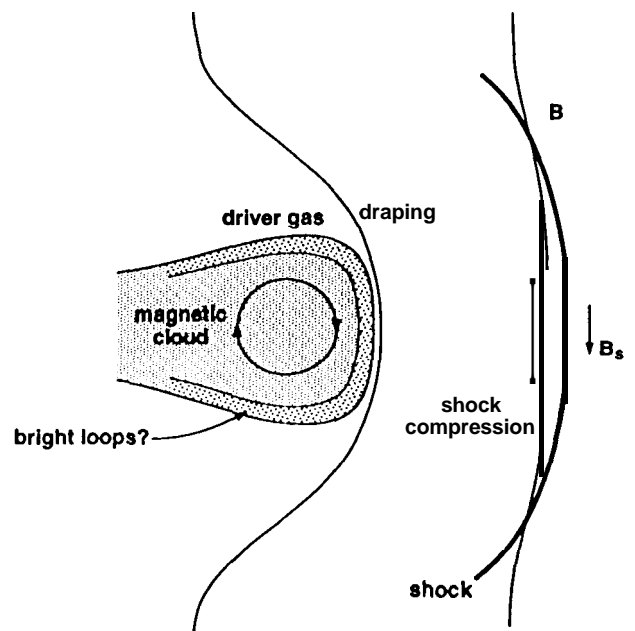


Fig. 1. Schematic showing geometry of a magnetic cloud

It has been shown that a southward IMF ≤ -10 nT (≥ 5 mV/m) for $T > 3$ hours is **necessary** for the creation of an intense ($D_{ST} \leq -100$ nT) magnetic storm (Gonzalez and Tsurutani, 1987). Although this empirical relationship was originally demonstrated for the solar maximum epoch, it has been shown to hold for solar minimum as well (Tsurutani et al., 1995).

The southward IMF events can be located either in the sheath fields ahead of fast interplanetary coronal mass ejections (ICMEs) or within the ICMEs themselves. The latter case, B_s within an ICME, is usually in the form of a magnetic cloud (Burlaga et al., 1981). A schematic of this overall geometry is given in Figure 1.

There are reasons to expect stronger magnetic fields in both interplanetary regions for fast ICMEs. A fast driver

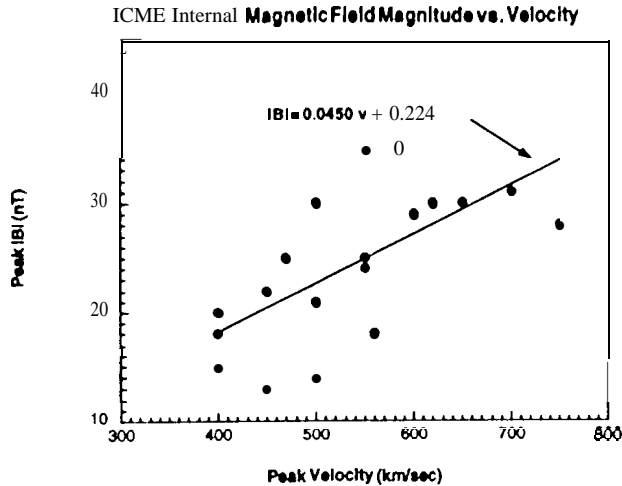


Fig. 2. Peak magnetic field magnitude ($|B|$) plotted against the peak magnetic cloud velocity (V) for 20 events.

gas will in general lead to stronger shock-compressed magnetic fields (depending on the upstream flow conditions). The magnetic field compression across the shock can be up to a maximum of 4 (Kennel et al., 1985). If the upstream IMF has a southward orientation, the shock leads to intensification of this component.

In our previous data analyses efforts, we had noted a general relationship between the speed of the ICME and the magnetic field intensity in the magnetic cloud. To examine this relationship quantitatively, we have used published examples of clouds from Klein and Burlaga (1982), Burlaga et al. (1987), Tsurutani et al. (1988, 1992), Burlaga et al. (1996), and Farrugia et al. (1997). Figure 2 displays the field peak intensity versus the peak cloud velocity for all of the above events when the plasma and field data were available. There is a clear tendency for the cloud to have higher magnetic fields the faster it is propagating.

At this time, the physical causes of the relationship between cloud $|B|$ and V_{sw} are uncertain. Compression of the cloud is certainly occurring, but it is uncertain whether all of the field increase can be accounted for by such an effect. Another possibility is that this relationship may be related to the CME release and acceleration mechanisms at the Sun. The $|B|$ - V_{sw} relationship may give important clues as to these mechanisms.

3 Shock Effects

One mechanism to create even higher field strengths would be for a second interplanetary shock to (further) compress the high fields existing in the ICME/sheath regions (of Figure I). An argument was presented in Tsurutani and Gonzalez (1997) that the presence of shocks/strong compressions may not be possible within magnetic clouds because of the low beta conditions present there. Typical beta values in clouds are ~ 0.1 with consequential Alfvén/magnetosonic speeds of 300-700 km

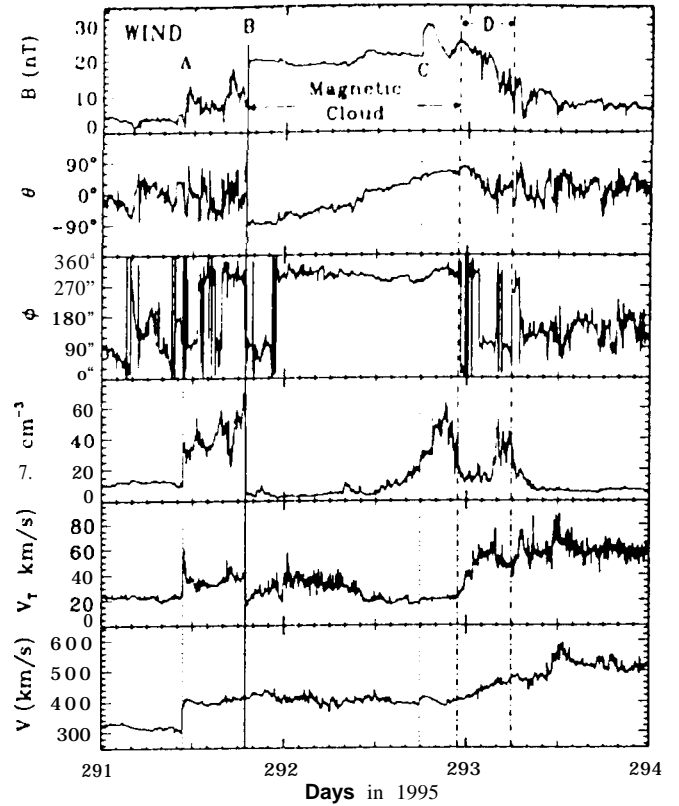


Fig. 3. Magnetic cloud event of October 18, 1995.

s^{-1} . These high speeds would ordinarily preclude the formation of shocks within magnetic clouds. However, somewhat surprisingly, a shock/compressional wave has been noted within a cloud in Lepping et al. (1997). A strong magnetic compression exists at point C in Figure 3. The field compression is $\sim 36\%$. There are coincident increases in plasma density and velocity. We note however, that the density at this time is $\sim 20 \text{ cm}^{-3}$, a value which decreases rapidly towards the front (antisolar) portion of the magnetic cloud. Thus the wave compression will decrease drastically as the wave propagates forward.

It is unclear what will happen to this wave when it reaches the other side of the cloud. It may be sufficiently dispersed or it may possibly reform as a shock. Another mechanism to have shocks occurring within sheaths is to have the shocks propagate from the downstream magnetosheath up into the front side sheath regions. To determine what the possibility of each of these mechanisms might be, simulation efforts are recommended.

Shock compression of sheath fields has been previously observed. Figure 4 shows the magnetic field for the August 1972 event at Pioneer 10 (2.2 AU). At this distance, the highest field strengths ($\sim 18 \text{ nT}$) are associated with this process. The first shock compresses the ambient magnetic field by ~ 4 times and the second shock by ~ 2 times. Exactly how this second shock was present in the sheath is not known.

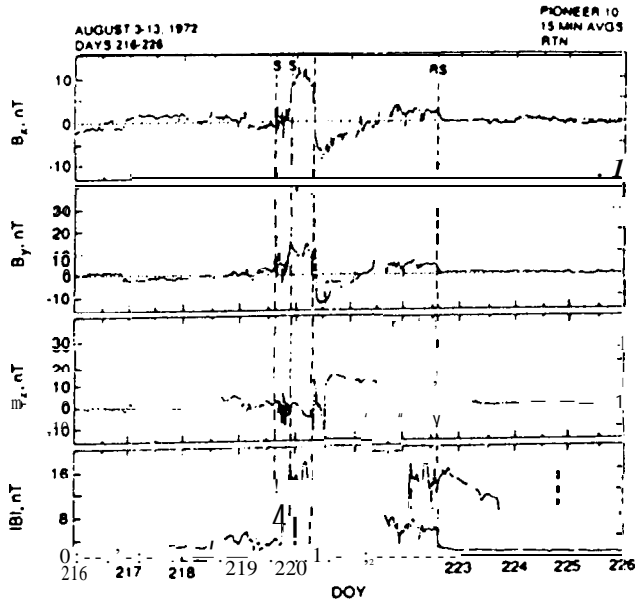


Fig. 4. Pioneer 10 IMF data at 2.2 AU from the Sun (from Smith et al., 1976).

The August 1972 interplanetary event had a velocity greater than 1500 km s^{-1} at 1 AU (the plasma instruments were saturated). The magnetic cloud field strength reached 16 nT at 2.2 AU, corresponding to 51 nT at 1 AU (assuming a $r^{-1.7}$ radial dependence). The field at 1 AU would be higher if a steeper dependence is assumed. Note that this $|B| \cdot V_{\text{sw}}$ relation is in general agreement with the trend of Figure 2.

4 Double Storms

Another way to get large D_{ST} events is to have two storm main phases with the second closely following the first. Kamide et al. (1997) in an analysis of more than 1200 magnetic storms has shown that such events are quite common and are caused by two IMF southward field events of approximately equal strength. This is shown in Figure 5. Kamide et al. argue that this could also be viewed as two moderate magnetic storms with the D_{ST} base of the second well below that of the first.

Grande et al. (1996) and Daglis et al. (1997) have studied the March 23, 1991 double magnetic storm using CRRES ion composition data. Grande et al. point out that the first event is dominated by Fe^{+9} , whereas the second by Fe^{+16} . A likely explanation is the first event was caused by sheath southward IMFs (shocked, slow solar wind plasma and fields) and the second was from the remnants of the ICME itself (magnetic cloud). The peak D_{ST} for the first event was -100 nT and -300 nT for the second event. We note however that these values were not pressure-corrected. The

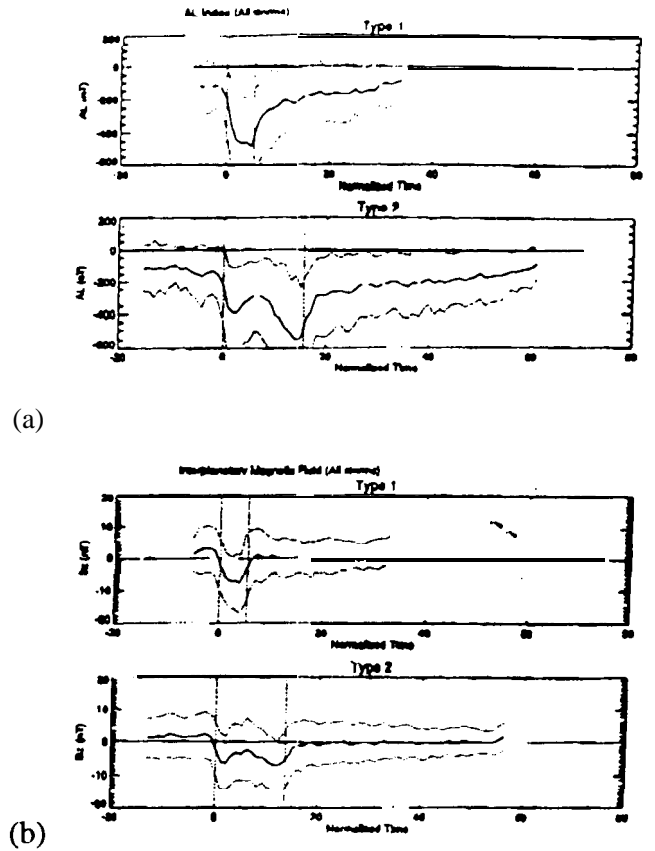


Fig. 5. Normalized time series of (a) the AL index showing the development of single (top panel) and double (second panel) geomagnetic storms, and (b) the corresponding IMF B_z components showing the southward turning of the field which induces the response in the AL index shown in (a).

field at the storm initial phase was -60 nT indicating that the correction will be substantial.

We reexamine the interplanetary causes of great magnetic storms ($D_{\text{ST}} \leq -250 \text{ nT}$) which have corresponding interplanetary data (reported in Tsurutani et al., 1992). The D_{ST} profiles are shown in Figure 6. Three of the four largest events have complex main phases. The April 12-13, 1981 and July 13-14, 1982 events are double main phase storms. The February 7-9, 1986 storm had a main phase that took 1 1/2 days to develop, then an abrupt further decrease. This could be due to a complex ICME sheath region.

5 Superintense ($D_{\text{ST}} \leq -400 \text{ nT}$) Magnetic Storms

Some of the largest magnetic storms registered since the D_{ST} index became available (1957) occurred in the 1957-1959 era. These events occurred prior to the advent of in situ space plasma measurements. However, with our recent knowledge of the interplanetary causes of magnetic storms, we can make an educated guess as to their interplanetary

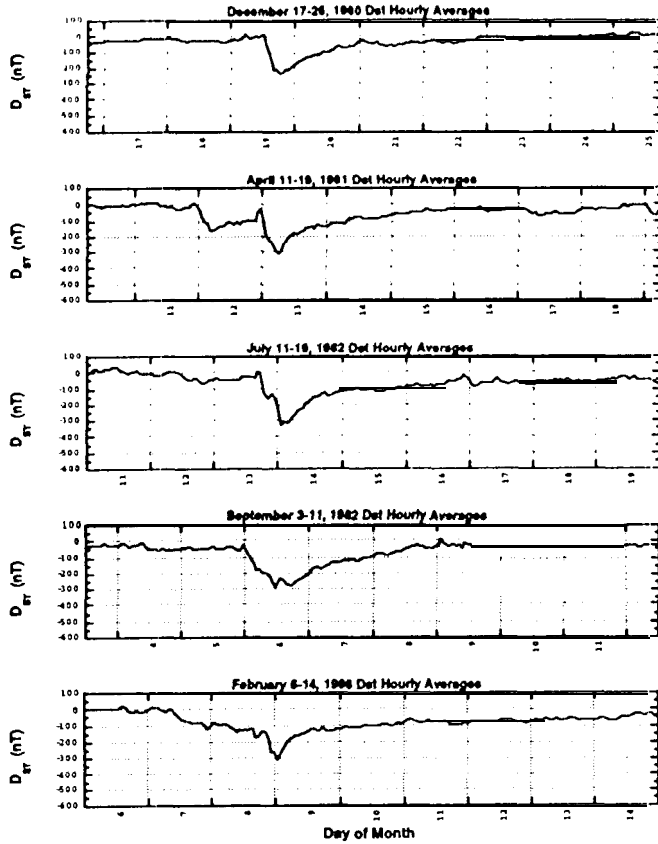


Fig. 6. The five largest magnetic storms during the period from 1980 through 1986.

causes. Figure 7 shows the profile of the three storms that had (uncorrected) peak D_{ST} values ≤ -400 nT. There is one event for each of the years 1957 through 1959. The main phases of each of the three storms are relatively short, all less than 12 hours. The July 15, 1959 event was clearly a

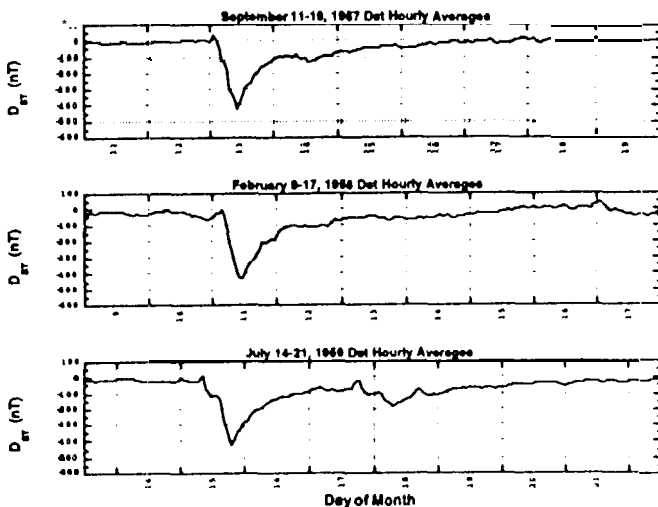


Fig. 7. The three largest magnetic storms during the period from 1957 through 1959.

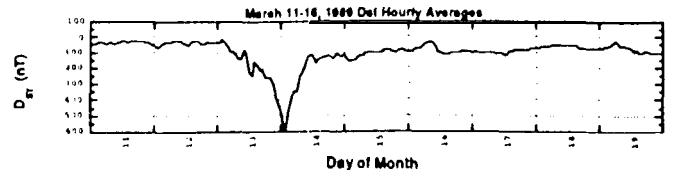


Fig. 8. The largest geomagnetic storm appearing in the D_{ST} record

double storm event.

We also display the March 13-14, 1989 event, the largest recorded during recent times ($D_{ST} \approx -600$ nT, uncorrected for pressure). This is shown in Figure 8. There is a slowly developing main phase prior to a sharp D_{ST} decrease at -20 UT day 13. This profile is similar to the February 7-9, 1986 event discussed previously. The whole main phase takes over 24 hours. This most certainly indicates the presence of a complex sheath region existing ahead of a magnetic cloud. The storm profile indicates that this may be viewed as a double storm event.

6 Conclusions

Although the 1957-1996 interval did not have sufficient interplanetary data available to examine the causes of all of the superintense storms, use of existing D_{ST} profiles can allow one to make reasonable hypotheses of the interplanetary causes of such events. It is found that double storms caused by two IMF B_s events are quite common and may contribute significantly to the occurrence of superintense storms. We found no evidence of double shock events causing $D_{ST} < -400$ nT magnetic storms. However, it should be noted that the storm sample used was quite limited.

Acknowledgment. Portions of this work were done at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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